Tolerable Beam Loss at High-Intensity Proton Machines

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Abstract

Tolerable beam losses are estimated for high-intensity ring accelerators with proton energy of 3 to 16 GeV. Dependence on beam energy, lattice and magnet geometry is studied via full Monte Carlo MARS14 simulations in lattice elements, shielding, tunnel and surrounding dirt with realistic geometry, materials and magnetic fields.

1 INTRODUCTION

Several high-intensity proton accelerators are under operation, construction or design all around the world. Their beam energy ranges from several hundred MeV to 50 GeV with the beam power of up to 4 MW. One of them is the Proton Driver (PD), a 16 GeV high-intensity rapid cycling proton synchrotron planned at Fermilab. There are many common problems at the machines of such a class. A very high beam power implies serious constrains on beam losses in the machine. The hands-on maintenance, component lifetime, ground-water activation and radiation shielding are the most important issues driven by beam loss rates under normal operation and accidental conditions. This paper estimates tolerable beam loss levels in a several GeV energy range.

2 REGULATORY REQUIREMENTS

1. *Prompt radiation:* the criterion for dose rate at non-controlled areas on accessible outside surfaces of the shield is 0.05 mrem/hr at normal operation and 1 mrem/hr for the worse case due to accidents [1]. Currently, the document [1] uses the phrase "credible accident". The one hour continuous maximum intensity loss was required in the past but is not required under all conditions anymore. In many cases, it is not even possible for a machine to do this. It is unfair to designers of future accelerators to force this requirement. The document [1] requires that the machine designers describe and justify what a possible credible worse case accident is, and design the shielding—or modify operation of the machine—according to that [2].

2. *Hands-on maintenance:* residual dose rate of 100 mrem/hr at 30 cm from the component surface, after 100 day irradiation at 4 hrs after shutdown. Averaged over the components dose rate should be less than 10-20 mrem/hr. It is worth to note that the (100 days / 4 hrs / 30 cm) condition is practically equivalent to the (30 days / 1 day / 0 cm) one.

3. *Ground-water activation:* do not exceed radionuclide concentration limits $C_{i,reg}$ of 20 pCi/ml for ^{3}H and 0.4 pCi/ml for ^{22}Na in any nearby drinking water supplies. These limits have the meaning that if water containing only one of the radionuclides at the limit were used by someone as their primary source of drinking water, that individual would receive an annual dose equivalent of 4 mrem.

4. *Component radiation damage:* machine component lifetime of 20 years. Assume 10 Mrad/yr in the hot spots.

3 GROUND-WATER ACTIVATION

Ref. [1] defines the concentration limits for the two long-lived isotopes that most easily leach and migrate to the ground water: ^{3}H (half time $\tau_{1/2}$=12.32 yr, β^- decay mode) and ^{22}Na ($\tau_{1/2}$=2.604 yr, β^+ and γ decay modes). One should calculate creation and build-up of those nuclides. After irradiation over the time t, the concentration of a radionuclide i in the ground water in soil immediately outside the beam loss region is

$$C_i\left(\frac{pCi}{ml}\right) = \frac{1}{0.037}N_pS_{av}\frac{K_iL_i(1-e^{-t/\tau_i})}{n},\qquad (1)$$

where N_p is the number of protons per second at the source, S_{av} is the star density above 50 MeV (stars/cm^3/proton) averaged over a volume surrounding the source out to an appropriate boundary (e. g., to 0.1% of the maximum star density at the entrance to the soil, that is a "99.9% star volume"), K_i is the radionuclide production yield (atoms/star), L_i is the leachability factor, n is the soil porosity, that is the ratio of the volume of void in the soil (generally filled with water), to the volume of rock (unitless), and τ_i is the mean lifetime of the radionuclide i, $\tau=\tau_{1/2}/\ln 2$. The K_iL_i and w_i are the site specific parameters. Taking the Fermilab NuMI project [3] as an example, one gets for the glacial till: K_{3H} L_{3H} = 0.075 atoms/star, K_{22Na} L_{22Na} = 0.0035 atoms/star, and n=0.30. The sum of the fractions of radionuclide contamination (relative to regulatory limits $C_{i,reg}$) must be less than one for all radionuclides [3, 4]:

$$C_{tot} = \sum_{i=1}^{N}\frac{R_iC_i}{C_{i,reg}} \le 1,\qquad (2)$$

where R_i is the reduction factor for the nuclide i due to vertical transport through the material surrounding the tunnel and horizontal transport in the aquifer. Usually, R_i is taken to be unity in such materials as dolomite, but $R_i < 1$ in glacial till and similar materials [4]. Using R_i=1 would therefore overestimate the result [2].

4 CALCULATION MODEL

The MARS code system [5] is used to perform all the calculations in this study. A new interface library has been developed—using ideas and code of Ref. [6]—which allows one to read and build complex machine geometry

directly from the MAD lattice description. The call-back mechanism is used to achieve such a goal. Namely, the user describes the geometry components at $\vec{r} = \vec{0}$ and unrotated, their field, materials and volumes as callable function with well-defined signature and registers them with the MAD interface code. Using information on lattice description, MAD generates rotation matrices and translation vectors for each particular elements together with glue elements. The call-back mechanism also allows one to register and call specific geometry, field and initialization function for any non-standard element in the lattice. The dipole, quadrupole and sextupole field components from the MAD lattice description are transfered to the respective field functions in order to correlate the field with lattice bending angle. An example of the PD pre-booster lattice geometry generated is shown in Fig. 1.

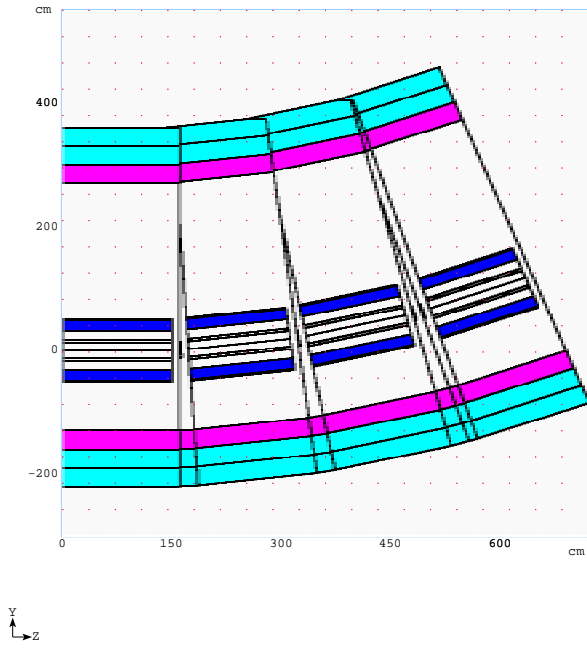Figure 2: MARS model of a Fermilab Booster arc cell.

Figure 1: MARS model of a PD 3 GeV pre-booster arc cell.

Using this MAD/MARS interface, the arc cells were built as per [7] and [8] for the Fermilab 8 GeV Booster(Fig. 2) and for the Proton Driver 3 GeV pre-booster (Fig. 1) and a 16 GeV ring. The lengths of the arc sections considered were about 20, 50 and 80 meters for 3, 8 and 16 GeV machines, respectively. The beam-lines include magnets, quadrupoles, bare beam-pipes (drifts) and tunnel geometry. The magnetic fields for the particular components were also implemented into the model. Typical cross-sectional views of the lattice elements in the calculation model are shown in Fig. 3 and Fig. 4.

As data and calculations show, beam loss distributions are quite different in different machines under given conditions. To deduct the tolerable beam loss, it is assumed in this study for all three machines that the beam loss rate is quasi-uniform along the considered arc region and that protons hit
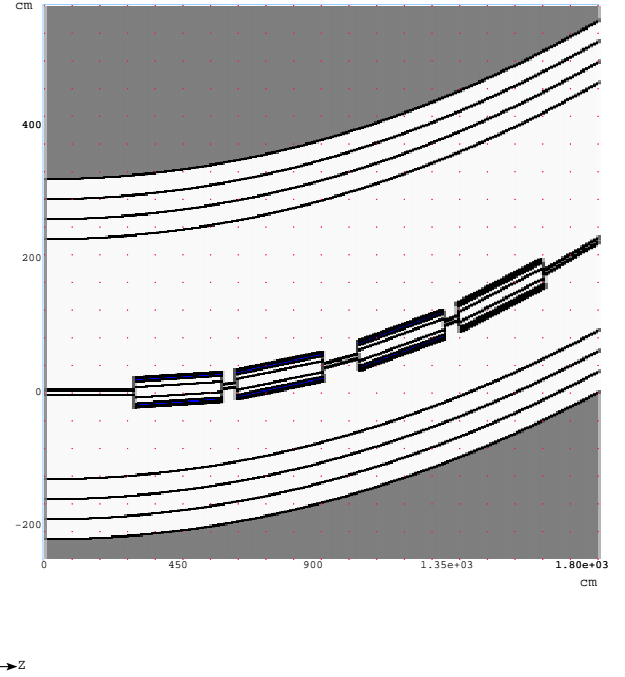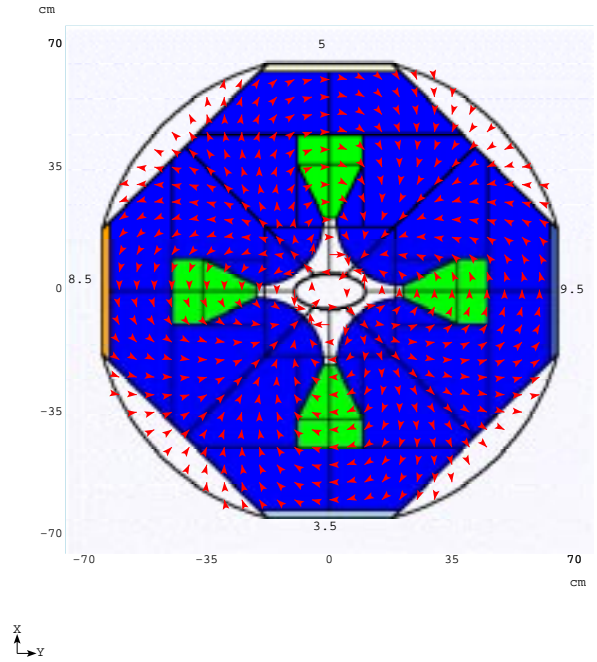

Figure 3: MARS model of 16 GeV PD quadrupole.

the beam-pipe under a grazing angle of 1 mrad horizontally inwards for the 3 and 16 GeV machines and vertically up for the 8 GeV Booster. More realistic source can certainly be generated with such a tracking code as STRUCT [9].

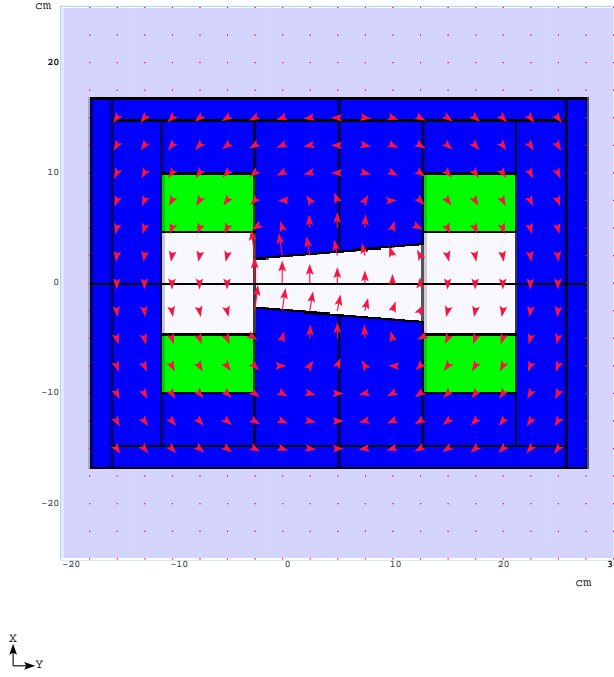Results of calculations are normalized per the beam loss of 1 W/m which is equivalent to

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Figure 4: MARS model of Fermilab Booster defoc magnet.

- $2.1 \cdot 10^9$ protons/(m·sec) for 3 GeV machine,

- $7.8 \cdot 10^8$ protons/(m·sec) for 8 GeV machine,

- $3.9 \cdot 10^8$ protons/(m·sec) for 16 GeV machine.

Calculated are energy deposition in dipole and quadrupole coils, star density near the magnet surface in order to deduce residual dose on contact using ω-factors for 30 days of irradiation and 1 day of cooling, averaged over the "99.9% volume" star density in soil to calculate the ground-water activation assuming a 20 yr irradiation time and the glacial till parameters with $R_i=1$, and dose equivalent distribution soil to estimate radiation shielding parameters.

5 RESULTS

5.1 16 GeV Proton Driver

Calculated peak residual dose rates on contact are shown in Fig. 5. The dose near the bare beam pipes exceeds the design goal for hot regions of 100 mrem/hr, being noticeably lower near the magnets due to significant absorption of soft photons in the dipole and quadrupole materials. One sees that hands-on maintenance is a serious issue with about 3 W/m as a tolerable maximum beam loss rate in the lattice elements, except for the long bare beam pipes where one should decrease the loss rate to 0.25 W/m to reduce the dose to 100 mrem/hr. One needs further reduction to bring the dose down to a good practice value of about 10-20 mrem/hr. Alternatively, one can think of providing simple shielding around the bare beam pipes. For ground-water activation

$C_{tot}=0.975$ immediately outside the 40-cm tunnel wall (see Eq. (2)), that allows 1.03 W/m beam loss rate. The peak accumulated dose in the coils is about 2 Mrad/yr at 1 W/m beam loss rate which is acceptable with use of appropriate materials for insulation.
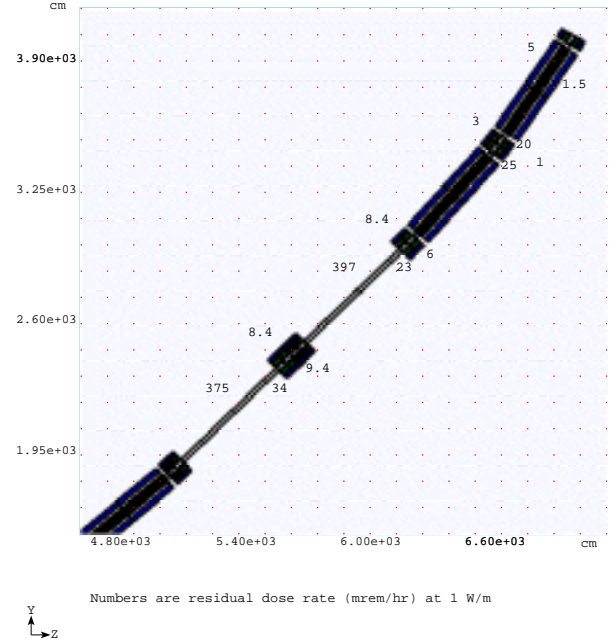

Figure 5: Peak residual dose rates (mrem/hr) on the outer surface of the arc elements at 1 W/m uniform beam loss rate in the 16 GeV Proton Driver.

5.2 Fermilab Booster

At 1 W/m uniform beam loss in the arcs, the peak residual dose rates on contact are up to 350 mrem/hr on bare beam-pipes and 6 to 12 mrem/hr on magnet surfaces. The peak accumulated dose in the coils is about 0.6 Mrad/yr. For ground water $C_{tot}=0.44$, that allows 2.27 W/m. Therefore, hands-on maintenance is the limiting factor for the Fermilab Booster and the tolerable beam loss rate is ≤ 0.3 W/m.

5.3 3 GeV Pre-booster

At 1 W/m uniform beam loss in the arcs, the peak residual dose rates on contact are up to 150 mrem/hr on bare beam-pipes and 7 to 14 mrem/hr on magnet surfaces. Compared to the 16-GeV case, dose on the pipes is lower because the drifts are shorter, only 12.5 cm. The peak accumulated dose in the coils is about 1.6 Mrad/yr. For ground water $C_{tot}=0.29$, that allows 3.45 W/m. The tolerable beam loss rate is ≤ 0.67 W/m.

6 TUNNEL SHIELDING

Another distinctive value is the amount of dirt required for tunnel shielding. Dose on the outer shielding surface depends on the beam energy in a complex way. Assuming a

quasi-local beam loss in the dipole magnet positioned in the center of a 2-m radius tunnel with a 0.3 m concrete wall, dose equivalent was calculated with MARS14 as a function of a dirt thickness ($\rho = 2.24$ g/cm^3). Fig. 6 shows this dependence for a 400 MeV beam (injection) and for three top beam energies considered in this paper under the same geometry, tunnel and beam conditions. As expected [10], dose at high energies scales as E^α, where α is about 0.8, while $\alpha \geq 1$ at proton energies below about 1 GeV.
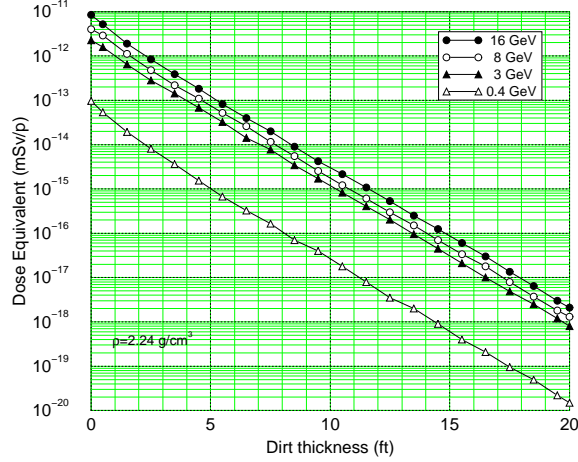

Figure 6: Prompt dose equivalent *vs* dirt thickness around the tunnel at a point-like loss of proton beams of different energies.

At the 16 GeV 15 Hz Proton Driver with 3×10^{13} circulating protons, the dose which corresponds to the 1 mrem limit for the worse case point-like loss of 1.62×10^{18} protons for an hour is $D_0 = 6.18 \times 10^{-24}$ Sv per proton (1 Sv = 100 Rem), requiring about 28 feet of the dirt shielding around the tunnel. With the accidental beam loss of 0.1% of the above—that can be defined as a *credible* accident for this machine—the shield thickness at 16 GeV is reduced to 18 feet.

7 CONCLUSIONS

- Each machine has different lattices, magnet geometry and materials, as well as properties of the soils around the tunnel. Beam loss distributions, driven by the collimation system performance (if such a system is implemented into the machine), are also quite different. Therefore, the tolerable beam loss should be determined for each machine individually together with the appropriate worse case beam loss scenario.

- In the cases studied in this paper, dose accumulated in the magnet coils is not a limiting factor.

- To meet the concentration limits immediately outside the 40-cm tunnel wall with the reduction factor $R_i=1$, the beam loss rates should be below than 1.03, 2.27

and 3.45 W/m in the arcs of the considered 16, 8 and 3-GeV machines, respectively.

- Hands-on maintenance is the limiting factor in all the considered cases, requiring beam loss rates in the arcs be as low as 0.1–0.25 W/m, if the beam-pipes are long and not shielded, and $\sim$1–3 W/m in the shielded case and in the magnets.

- Radiation shielding thickness scales non-linearly with the beam energy below about 1 GeV.

8 REFERENCES

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